Chapter 1: Executive Summary

1.0 Overview

The H-mode confinement regime is characterized by a region of good thermal and particle confinement at the edge of the confined plasma, and has generally been envisioned as the operating regime for ITER and other next step devices. This good confinement is often interrupted, however, by edge-localized instabilities, known as ELMs. On the one hand, these ELMs provide particle and impurity flushing from the plasma core, a beneficial effect facilitating density control and stationary operation. On the other hand, the ELMs result in a substantial fraction of the edge stored energy flowing in bursts to the divertor and first wall; this impulsive thermal loading would result in unacceptable erosion of these material surfaces if it is not arrested. Hence, developing and understanding operating regimes that have the energy confinement of standard H-mode and the stationarity that is provided by ELMs, while at the same time eliminating the impulsive thermal loading of large ELMs, is the focus of the 2013 OFES Joint Research Target (JRT):

Annual Target:

Conduct experiments and analysis on major fusion facilities, to evaluate stationary enhanced confinement regimes without large Edge Localized Modes (ELMs), and to improve understanding of the underlying physical mechanisms that allow acceptable edge particle transport while maintaining a strong thermal transport barrier. Mechanisms to be investigated can include intrinsic continuous edge plasma modes and externally applied 3D fields. Candidate regimes and techniques have been pioneered by each of the three major US facilities (C-Mod, D3D and NSTX). Coordinated experiments, measurements, and analysis will be carried out to assess and understand the operational space for the regimes. Exploiting the complementary parameters and tools of the devices, joint teams will aim to more closely approach key dimensionless parameters of ITER, and to identify correlations between edge fluctuations and transport. The role of rotation will be investigated. The research will strengthen the basis for extrapolation of stationary regimes which combine high energy confinement with good particle and impurity control, to ITER and other future fusion facilities for which avoidance of large ELMs is a critical issue.

Data from the Alcator C-Mod tokamak (MIT), DIII-D tokamak (General Atomics), and NSTX spherical tokamak (PPPL) contribute to this report. Experiments specifically motivated by this research target were conducted on DIII-D, with a national team of researchers from GA, LLNL, PPPL, MIT and ORNL contributing. Both the Alcator C-Mod and NSTX-U teams contributed analysis of previously collected data, as those two facilities did not operate in FY2013. Within each of the three research groups, members from both the host institutions and collaborating institutions made critical contributions. Highlights from these research activities are provided below, with additional details provided in chapters 2-5.

2.0 Highlights from the Alcator C-Mod Contributions

Alcator C-Mod contributions to the JRT focus on the I-mode confinement regime. This regime is characterized by H-mode like temperature pedestals, but L-mode like edge density profiles. As a consequence, ELMs are largely absent in this regime. Particle and impurity transport is provided by a broadband edge fluctuation known as the Weakly Coherent Mode (WCM). Normalized energy confinement at the level needed for ITER has been obtained at low safety factor q_{95} and collisionality. The upper limit in plasma pressure is set either by transitions to H-mode or by available heating power. Stability calculations, and initial experiments with density control, indicate potential to further expand the operating regime to higher density and pressure.

Highlights from the C-Mod contribution towards understanding the physics mechanisms of the particle and thermal transport, and the absence of ELMs, include:

- In the area of assessing operating space and extrapolability of the I-mode regime, databases of global and pedestal I-mode parameters have been significantly expanded to a wide range of plasma dimensional (magnetic field, current, density and power) and dimensionless parameters.
- A major emphasis of 2013 research has been the analysis of profiles in the plasma edge; an extensive recalibration of the edge Thomson scattering system was completed as part of this process. This has revealed that I-mode pedestals are wider than those in H-mode, with widths up to 5% of the poloidal flux. This pedestal width does not follow any clear trend with $\beta_{P,ped}$, unlike in H-mode where a $\beta_{P,ped}^{1/2}$ scaling of the width was observed.
- These profiles have been used for edge stability analysis with the ELITE code. As anticipated from their ELM-free nature, these regimes are far from the MHD stability boundary, potentially allowing for further increases in performance.
- Gyrokinetic stability calculations have been performed using GYRO and GS2; excellent agreement has been found between the codes for the growth rates and real frequencies. Promising results include linearly unstable modes in the k_θ and frequency range of the observed WCM, propagating in the electron diamagnetic direction.
- Considerable progress has been made studying the relationship between pedestal turbulence and transport. There is a reduction in 60-150 kHz broadband turbulence following the L→I transition, accompanied by the formation of T_e and T_i pedestals; this is in contrast to the typical increase in turbulence in this frequency range following an increase in heating power in L-mode.

- The decrease in lower frequency turbulence is accompanied in I-mode by an increase in turbulence in the range 150<f [kHz]<300. These, Weakly Coherent Mode (WCM) fluctuations, have $\delta T_e/T_e$~2% (from ECE), but $\delta n_e/n_e$~10%, potentially consistent with the WCM driving more particle than energy transport.
- The WCM fluctuation amplitude has been found to be proportional to the particle flux in experiments where the plasma current was held fixed and the heating power varied. This provides strong evidence that the WCM provides critical contributions to the edge particle transport.
- Geodesic Acoustic Modes (GAMs) have been observed for the first time in Alcator C-Mod, in I-mode discharges; indeed, these fluctuations are present in all I-mode discharges analyzed to date that have GPI data available. These ~20 kHz GAMs interact and exchange energy with the WCM, and this fluctuating flow may be responsible for the broad frequency of the WCM.
- A reduction of core turbulence in I-mode has also been observed. The density fluctuation level $\delta n_e/n_e$ can decrease by 30%, and reductions in temperature fluctuations at the innermost point (ρ=0.74) have also been observed.

These C-Mod results are described in greater detail in Chapter 3.

3.0 Highlights from DIII-D Contributions

DIII-D contributions to the 2013 JRT came across a range of plasma configurations, targeting a range of physics goals. Specific regimes under consideration include:

- RMP studies: Resonant Magnetic Perturbations (RMP) are an important technique to control the H-mode edge transport and avoid type-I ELMs. In these experiments 3D fields of various types are applied to the plasma, creating 3D distortions, and potentially magnetic islands and magnetic stochasticity. These effects limit the width of the pedestal, thus avoiding the onset of type-I ELMs. This is a well established regime in DIII-D, and is now extended to ITER's I_p/aB_T.
- QH-mode: The Quiescent H-mode operating regime has H-mode like confinement, with pedestals in both the temperature and density, but with no large ELMs. Edge particle and impurity transport is provided by an Edge Harmonic Oscillation (EHO). This regime is also a well established in DIII-D, operating close to ITER-relevant torque and performance levels, and now extended to ITER-relevant Greenwald fractions.
- I-mode: The I-mode regime was described in section 2.0 of this chapter. A number of cases with temperature pedestals but no density barrier have been demonstrated in initial DIII-D experiments, although confinement is not yet as high as on C-Mod.
- VH-mode: The VH-mode is a very high confinement, ELM-free regime observed in DIII-D, with $H_{98(y,2)}$ up to 1.8. These regimes are associated with expanded pedestal widths and broader regions of flow shear, but with density accumulation rendering them non-stationary; arresting this density rise was a key goal of experiments in FY-13.

Given these various plasma regimes, experiments were conducted to both understand the transport physics and to test the physics limits of the operational regimes.

In the area of understanding the physics mechanisms that can provide the necessary particle transport in the absence of ELMs, the following key observations have been made:

- Experiments using fluorine as a tracer impurity were conducted to understand the impurity flushing in Q-mode. These experiments showed that the EHO in QH-mode can actually flush edge impurities more efficiently than type-I ELMs. Furthermore, the impurity confinement time does not increase as the toroidal rotation is reduced at constant density, despite the significant improvement in energy confinement/
- Experiments designed to explore and understand I-mode transport physics in DIII-D were executed. Numerous I-mode candidate examples were found in discharges with power ramps, distinguished by cases where the edge temperature increases by a fraction larger than the associated increase in the input power. These are not H-mode transitions, although the D_α recycling light indicates a complex evolution, as do related density fluctuations as measured by BES. These fluctuations are presently being analyzed and compared to type-III ELM regimes.

In the area of extending the operating space of these attractive regimes, the following key contributions are documented in this report:

- Experiments explored the achievable I-mode operating space by varying key parameters (I_P, q_{95}, δ_L, and κ). As noted above, a range of I-mode scenarios were identified. However, the observed confinement in these cases was less than in C-Mod, with $H_{98(y,2)}$<0.75 in all cases. Preliminary assessment shows that the expected pedestal evolution was cut short by sawtooth-triggered I->H transitions. This conclusion is reinforced by the observation that the lowest plasma currents had the higher electron temperature. These lower I_P cases had smaller sawtooth heat pulses, allowing the pedestal temperature to reach higher values before the H-mode transition. This effect is strong enough to overcome the degradation of the pedestal temperature with decreasing I_P, as observed in the C-Mod I-modes. As observed on Alcator C-Mod, the I-mode pedestal were found to be wider than H-mode pedestals, and wider than suggested by the EPED $\beta_P^{1/2}$ scaling.
- Experiments were conducted with the goal of extending QH-mode operation to high-normalized fusion performance. QH-mode performance corresponding to Q=10 in ITER was demonstrated for q_{95}=3.2, but only at high counter neutral beam torque. Reducing the counter torque results in locked mode formation. The toque threshold for locking was lower at higher q_{95}, and the NB torque can be reduced to zero at q_{95}=4.7 without locked mode onset.
- An additional set of experiments focused on increasing the density in QH-mode. As anticipated, no correlation with the Greenwald density limit was found, and Greenwald fractions of ~80% have been achieved with strong shaping. This is

consistent with ELITE calculations, which indicate that strong shaping expands the kink/peeling stability boundary to higher pressure and current.

- VH-mode experiments were conducted in order to i) attempt to extend the duration of the VH-mode phase via the application of 3D fields, and ii) make comparison to the NSTX EP H-mode regime. Several high-quality VH-mode examples were produced, and their equilibrium and fluctuation characteristics documented with the state of the art DIII-D diagnostic set. However, subsequent attempts to extend the duration with n=3 fields were unsuccessful, with the 3D fields apparently hastening the onset of ELMs in some cases. Density pump-out was not observed in the VH-mode phase, possibly due to the relatively high collisionality and q_{95} of these plasmas.
- An experiment was conducted to understand RMP ELM suppression with less than the full set of 3D field coils (I-coils in this case). These experiments showed that ELM suppression could be achieved with only very modest increases in coil current as the number of coils decreased. This is likely due to the n=1 & 2 sidebands produced when a coil is removed, which could help to increase the magnetic stochasticity in the edge plasma.

These DIII-D results are described in greater detail in Chapter 4.

4.0 Highlights from the NSTX-U Contributions

NSTX-U contributions to the 2013 JRT come in three distinct physics areas: the enhanced pedestal H-mode (EP H-mode), improved understanding of transport in the ELM-free pedestal, and better understanding of observed Edge Harmonic Oscillations.

The EP H-mode is a confinement regime showing a separation between the thermal and particle transport, in this case manifest as a significant reduction in thermal transport beyond the level achieved in H-mode. Key observations presented in this report include.

- An automated analysis program was used to identify a large number of additional EP H-mode examples. These include a newly observed, quiescent long-pulse case.
- A wider range of EP H-mode edge profiles shapes has been observed compared to previous examples, from cases with the steep gradient region located at the very edge of the plasma, to cases where it is shifted inward by ~10 cm.
- The correlation of the EP H-mode ion temperature gradient with the edge rotation shear has been confirmed for a much larger database of EP H-mode examples.
- A comprehensive analysis of edge fluctuations in EP H-mode has been conducted. However, no clear changes in the fluctuations have been observed.
- Prospects for triggering EP H-mode in NSTX-U have been addressed. A scheme to trigger EP H-modes via a single triggered ELM appears feasible.

NSTX has a high performance ELM-free regime with Lithium conditioning of the PFCs. While this regime does have some impurity accumulation, understanding those impurity and transport dynamics can be critical for devising mechanisms to eliminate those undesirable features. Key observations presented in this report include:

- The lack of ELMs, along with changes to the carbon transport due to modifications of the main-ion temperature and density profiles, explains the core carbon accumulation in discharge with lithium PFC conditioning, though anomalous carbon transport in the pedestal is required to explain the details of the profile shapes. The enhancement of neoclassical lithium diffusivities due to the high carbon concentration is partly responsible for the low lithium core concentration.
- Experimental analysis of pedestal turbulence amplitudes from beam emission spectroscopy show trends consistent with TEM/KBM turbulence drives; the trends are notably inconsistent with a ITG driven turbulence. These trends are consistent with linear microstability calculations made with the GENE code.

Regimes such as the QH-mode and I-mode have shows that the global particle inventory can be regulated by edge fluctuations that take the place of ELMs. NSTX has had similar edge fluctuations, though their amplitude appears to be too small to influence the global transport. Key observations presented in this report include:

- Measurements of the mode structure from Beam Emission Spectroscopy and reflectometry confirm that these modes are indeed located at the plasma edge, with maximum amplitude near the separatrix.
- The pedestal stability of an example discharge has been examined, and the operating point is near the peeling boundary, as in QH-mode in DIII-D.
- Studies of the potential to drive EHOs using the NSTX-U HHFW antenna show that it may be possible, especially at low q_{95}, though the driven amplitudes may be smaller than what could have been possible in NSTX.

These NSTX results are described in greater detail in Chapter 5.

5.0 Implications for ITER

RMP ELM control offers strong prospects for providing a stationary, ELM-free regime for ITER, and has been adopted as part of the baseline design. It has been adapted to ITER conditions (shape, I_P/aB_T, collisionality, beta), and demonstrated with various coil configurations. Indeed experience around the world has shown a very wide range of different coil configurations have strongly beneficial effects to reduce the ELM size (if not always completely suppressing them). Work must continue to focus on physics mechanisms and extension to low torque, to provide fuller confidence of its applicability in ITER.

QH-mode provides prospects for an ELM free regime with high performance; when using the Neoclassical Toroidal Viscosity (NTV) effect, extension of this regime to low torque has been demonstrated. Further, the 3D fields used to generate the strong shear in the plasma edge that saturates the ELM precursor also appear to create increased core confinement. The regime has now also been extended to high Greenwald density fraction, and the role of the Edge Harmonic Oscillation (EHO) for expelling impurities was demonstrated. Nevertheless, confidence for ITER rests in gaining a predictive understanding of the EHO behavior onset, saturation and induced transport; demonstration of the regime on multiple devices would greatly assist this goal.

I-mode has the highly advantageous property of H-mode thermal confinement and L-mode particle confinement. It has been demonstrated in C-Mod to operate at the ITER q_{95} with high performance, and shows high confinement at ITER-relevant low collisionality and external torque. While there are no known physics barriers to extrapolate the I-mode regime to burning plasmas, projection of this regime to ITER requires an improved understanding of the physics governing the onset and saturation of the Weakly Coherent Mode (WCM), as well as the transport driven by these fluctuations. Refinement of techniques to avoid I→H transitions is needed. Continued multi-machine comparisons will be critical in making progress in this area.

VH-mode and EP H-mode both offer access to very broad pedestals and very high performance. However, their application to ITER remains more speculative. In particular, means of regulating the profile build-up must be developed, in order to arrest the density ramp and impurity accumulation. Furthermore, mechanisms of reliably triggering the EP H-mode configuration must be developed.

In conclusion, these various techniques offer increased optimism for the achievement and practical implementation of stationary ELM-free regimes in ITER, particularly with its flexible 3D coil set and other tools. Results in 2013 have made key further steps towards more ITER-relevant parameters, and addressed some key elements in the underlying physics. But in each case there is more to do, particularly to understand the physics of the mechanisms involved and to demonstrate robust control at the most ITER-relevant parameters.